Evaluation and Calibration of CERES3 (maize) : Kernel number simulation

A.S du Toit, ARC-Grain Crops Institute , Private Bag X1251, Potchefstroom, South Africa, 2520

South Africa produces an average of 6 million tons of maize annually, with a standard deviation of 2 million tons. This indicates that maize is produced in environmental conditions which rapidly change from one season to another. Yield is highly correlated with kernel number. To enable CERES-Maize to simulate this variation in maize yield, kernel number simulation needs to be accurate. Kernel number simulation by CERES-Maize was reported in literature as one of the variables that are simulated with low accuracy. This was confirmed in a study involving the evaluation of historical data. Results for the calibration consisted of data from trials of six row widths, over three seasons and a plant population trial of five cultivars x four plant populations for one season. The simulation of kernel numbers of the first, second and tiller ears were split and by including the number of days from silking to the commencement of active kernel growth, it was possible to improve the simulation of kernel number by CERES3. The original function for kernel number simulation indicated low sensitivity to water stress from silking to the commencement of active kernel growth. With the modifications made to CERES3, this sensitivity was increased. The D-index for kernel simulation was increased from 0.11 to a value of 0.87.

INTRODUCTION

Kernel number is an important component of grain yield and is sensitive to environmental stresses occurring near the silking date (Claasen and Shaw, 1970; Jones and Kiniry 1986). Loss in yield of 7% per water stress day during silking has been reported by Mallet (1972). Schussler and Westgate (1991) reported a decrease of up to 99% in kernel number with severe water stress occurring during silking. This could be explained by the fact that in maize, the number of kernels is mainly related to the current flux of assimilates around silking (Edmeades and Daynard, 1979). Herrero and Johnson (1981) observed that drought during silking had a greater effect on female than male floral development. Bassetti and Westgate (1993) reported a decrease in kernel number caused by the loss of silk receptivity during water deficits, whereas Otegui, Andrade and Suero (1995) ascribed this phenomenon to kernel abortion.

CERES-Maize uses the average rate of photosynthesis (PSKER) for the first 170 growing degree days from silking to calculate kernel number per plant (Jones and Kiniry, 1986). The Grant (1989) simulation uses the same approach but uses 320 growing degree days from silking in the calculation of kernel number. SUCROSE87 (Spitters, van Keulen and Kraailingen, 1989) and PUTU (De Jager, 1989) use the same approach as CORNF (Stapper and Arkin, 1980) where kernel number is estimated on the basis of the amount of biomass at anthesis.

Low accuracy in the simulation of kernel number has been reported by Carberry, Muchow and McCown (1989) for CERES-Maize v1.0. when using Edmeades and Daynard's (1979) hyperbolic function. The hyperbolic function in CERES-Maize v1.0 was replaced by a linear GPP function from CYMKEN (Keating, McCown & Wafula, 1993) for CERES-Maize v2.1. Results by Ogoshi (1995) for CERES-Maize v2.1. indicated a low accuracy of kernel number simulation with a r^2 of 0.31. The purpose of the present study was to improve the simulation of kernel number by means of further calibration of CERES3.

MATERIALS AND METHODS

Field trial

Previously conducted field trials pertaining to row width and plant population were used in combination, for evaluation and calibration of CERES3. The row width trial was the same as that used by Du Toit, Booysen & Human (1994) conducted in 1990/91. It consisted of six row widths viz 0.8, 1.0, 1.5, 2.0, 2.5 and 3.0 m rows at a plant population of 1.5 plants m^{-2}. The trial was repeated in the 1991/92 and 1992/93 seasons. The trial site was Ottosdal (26°00'S 26°57'E) in the absence of irrigation.

A further trial (1993/94) consisting of five cultivars was planted at Potchefstroom

($27^{o}04'S$ $26^{o}42'E$), with plant populations of 0.25, 1.0, 4.0 and 12,5 plant m^{-2}. In this trial square planting was used with spacings of 2.0, 1.0, 0.5 and 0.25 m. The trial was a complete randomised block design with three replications. Fertilizer of 37.5 (N), 25 (P) and 12.5 (K) kg ha^{-1} was applied at planting followed by 40 kg ha^{-1} N applied four weeks after planting for 0.25 and 1.0 plants m^{-2}, 80 kg ha^{-1} N for 4.0 plants m^{-2} and 120 kg ha^{-1} N for the 125 plants m^{-2}.

A field trial (Potchefstroom, 1986) pertaining six cultivars and three planting dates was used as independent data set.

Model modifications

In the standard CERES3 (phenol subroutine) kernel number (GPP) is calculated using the following function:

GPP = G2*PSKER/7200.0 + 50.0 (1)

The process of developing functions (two to eight) used in the modified CERES3 is as follows:

1. Testing function (1) in the standard CERES3 to determine if it can be used in the simulation of the kernel number of the first and second ear by just changing the coefficients 7200.0 and 50.0 with non-linear regression.

2. Identify the period (CDAY) between silking and the commencement of effective kernel filling (ISTAGE 4) as a possible factor that may by used to improve the simulation of the kernel number of the first and second ear.

3. The following algorithms were developed, including CDAY in the calculation of kernel number for the first and second ear:

   a. If the period between silking and the beginning of effective kernel filling (ISTAGE 4) is less than 12 days (CDAYS), GPP1 (Kernel number of the main ear) and GPP2 (Kernel number of the secondary ear) are calculated as follows:

GPP1= G2*PSKER/34451.66 + 190.82 (2)
(r^2=0.94)

GPP2= -475+4.84*PSKER**0.5 (3)
(r^2=0.92)

   b. If CDAY is equal to 12 days for ISTAGE 4, GPP1 and GPP2 are calculated form kernel growth rate of the first ear (G2) and the second ear (G22) as follows:

GPP1=(1-EXP(-0.000115*PSKER))*G2 (4)
(r^2=0.83)

GPP2=(1-EXP(-0.0000762*PSKER))*G22 (5)
(r^2=0.64)

   c. When CDAY exceeds 12 days GPP1 and GPP2 are calculated as follows:

GPP1=(1-EXP(-0.000143*PSKER))*G2 (6)
(r^2=0.66)

GPP2=(1-EXP(-0.000114*PSKER))*G22 (7)
(r^2=0.69)

GPP1 can not exceed G2 or be less than zero. GPP2 can not exceed G22 and be less than zero. A correction function for different row widths (ROWSPC) was included, calculated as follows:

GPP=GPP*1.41*EXP(-0.23*ROWSPC) (8)
(r^2=0.90)

GPP has been limited to 9% of PSKER.

RESULTS AND DISCUSSION

As a first step in improving the simulation of kernel number, coefficients (7200.0 and 50.0) in function 1 were replaced by coefficients calculated by means of non-linear regression, resulting in functions 9 and 10.

GPP1=G2*PSKER/46895.0 + 307.74 (9)
(r^2=0.37)

GPP2=G22 * PSKER/27604.0+38.40 (10)
(r^2=0.41)

The low value of r^2 obtained for these two functions indicate that the calibration of function 1 was not adequate to improve the simulation of kernel number and the consequent improvement of yield simulation.

Hall, Chimenti, Trapani, Vilella and Cohen de Hunau (1984) found a significant correlation between kernel number and the duration (in days) of silk exposure to pollen (CDAY). In

CERES3 the period from silking to the beginning of effective kernel filling (ISTAGE 4) is 170 degree days. Although CDAY is simulated in CERES3 it is not used in the simulation of kernel number. In the second step of improving kernel number simulation, the result of Hall *et al.* (1984) that kernel number is affected by CDAY was tested, before inclusion in CERES3.

The results in Table 1 confirm a significant interaction between kernel numbers of the first ear (GPP1) and second ear (GPP2), with both PSKER and CDAY. As expected, the interactions of both G2 and G22 with PSKER were not significant, since these two genetic coefficients are not functionary of environmental effects. The low correlation interaction between CDAY and PSKER shows that the contribution of CDAY to the calculation of kernel number was truly independent and therefore not confined in PSKER. The results indicate that the effect of CDAY on kernel number is applicable to these datasets.

Table 1. Correlation and level of interaction matrix.

	G22	GPP1	GPP2	Cday	PSKER
G2	0.79 ***	0.19 ns	0.33 *	-0.07 ns	-0.013 ns
G22	1	0.05 ns	0.40 *	-0.16 ns	0.16 ns
GPP1		1	0.58 *	0.38 *	0.58 ***
GPP2			1	0.33 *	0.57 ***
CDAY				1	0.13 ns

Since CDAY had a significant influence on kernel number, it could be used with G1, G2 and PSKER to calculate GPP1 and GPP2. Functions 11 and 12 were developed, using multiple regression to calculate GPP1 and GPP2 from G2, G22, PSKER and CDAY. With the inclusion of CDAY in the simulation of GPP1 it was possible to increase the r^2 value from 0.37 in function 9 to 0.54 in function 11, thus improving accuracy. This was also the case with the simulation of GPP2 (function 10 and function 12)

GPP1 = -1235.86+ 1.078 * G2- 0.42 * G22 + 86.67 * CDAY + 0.0128 * PSKER (11) (r^2=0.56)

GPP2 = -1779.72 + 0.400 * G2 + 0.217 * G22 +126.92 * CDAY + 0.012 * PSKER (12) (r^2=0.54)

Both PSKER and CDAY showed significant interaction with GPP1 in Table 2. The observation that the interaction between G2 and GPP1 was non significant, is an indication that for this specific calibration data set, the environmental differences were greater than cultivar differences. The significant contribution of CDAY in calculation of GPP1 is an indication that it needs to be included in the simulation of kernel number.

Table 2. ANOVA for function 12 to indicate the level of interaction of G2, G22, days and PSKER with kernel number of the first ear (GPP1).

Source	SS	df	MS	F	P
Total	540113	37			
Regression	304896	4	76224	10.69	**
G2	19942	1	19943	2.80	ns
G22	15890	1	15890	2.23	ns
CDAY	76061	1	76061	10.67	**
PSKER	193002	1	193003	27.08	**
Error	19942	33	7128		

* $P < 0.05$ ** $P < 0.01$

The interactions in Table.3 show the same trend as in Table 2 except for the interaction of G2 with GPP2. As in the case of Table 1 CDAY contributed significantly to kernel number calculation, therefore CDAY days should be included in the simulation of both GPP1 and GPP2. The observation that the interaction of PSKER with GPP1 (Table 2) and GPP2 (Table 3) was highly significant, is evidence in favour of the original hypotheses in CERES Maize (Jones & Kiniry, 1986), that PSKER should be used in the calculation of kernel number.

Table 3. ANOVA for function 13 to indicate the level of interaction of G2, G22, days and PSKER with kernel number of the second ear (GPP2).

Source	SS	df	MS	F	P
Total	784750	37			
Regression	423544	4	105886	9.67	**
G2	87147	1	87147	7.96	**
G22	36011	1	36011	3.29	Ns
CDAY	129425	1	129425	11.82	**
PSKER	170961	1	170961	15.62	**
Error	361207	33	10946		

* $P < 0.05$ ** $P < 0.01$

Based on the above results that CDAY contributed significantly to the calculation of kernel number, CDAY was categorised into three periods. Functions 2 and 3 are used when CDAY is less than 12 days. This improved the accuracy of kernel number simulation as was apparent by comparison of the r^2 values of functions 2 and 3 with the values of either functions 9 and 10 or 11 and 12. The r^2 values of the simulation of GPP1 and GPP2 by functions 4 and 5 also improved if CDAY equaled 12 days. For the third period the r^2 values of function 6 and 7 also improved when CDAY was greater than 12 days. Because of the improved r^2 values obtained for functions 2 to 7, it replaced function 1 of the standard CERES3 in the modified CERES3. The non-linear functions 2 to 7 provided higher values of r^2 as indicated by the comparison of the r^2 values of functions 2 and 3 with those of functions 9 and 10.

Table 4 provides a comparison of the simulation of kernel number by the standard and the modified CERES3 using an independent Pothefstroom 1986 data set. The accuracy in the simulation of kernel numbers was greatly improved as is indicated by the D-index and r^2 values. RMSE (Root mean square error) and RMSEs (sistematic) were reduced in the modified CERES3, but RMSEu (unsistematic) increased, which can be explained by the increase in the number of functions used for simulation of kernel number had increased from one to six.

Table 4 Quantitative measures of kernel number simulating by both the standard and modified CERES3, Potchefstroom trial (1986/87).

	Observed	Standard	Modified
Minimum	419	990	603
Maximum	1566	1105	1737
Mean	1049	1050	1216
Stdev	352	35	360
Slope		0.08	0.84
Intercept		959	21.82
Mae		299	205
RMSE		343	246
RMSEs		341	173
RMSEu		34	176
D-Index		0.11	0.87
R^2		0.001	0.74

CONCLUSION

The accuracy in the simulation of kernel number improved for both the data used for calibration and for the independent data set. This study indicated that the number of days (CDAY) from silking to effective kernel filling (ISTAGE 4) had a significant influence on the number of kernels produced by the maize plant. By including CDAY as a factor for the simulation of kernel number, it was possible to increase the accuracy of kernel number simulation.

Water stress during ISTAGE 4 should decrease PSKER and consequently lead to a decrease in kernel number. The original function (1) showed low sensitivity of kernel number over a wide range of PSKER values. With the calibration applied in this paper the sensitivity was improved significantly.

References

Basseti, P and M.E. Westgate, 1993. Water deficit affects receptivity of maize silks. *Crop Sci.* 33, 279-282, 1993.

Carberry, P.S., Muchow, R.E. and R.L, McCown, Testing the CERES-Maize simulation model in a semiarid tropical environment. *Field Crops Res.* 20:297-315., 1989.

Claasen,, M.M. and R.H. Shaw. Water deficit effects on Corn. II. Grain Components. *Agron. J.* 62,652-655, 1970.

De Jager, J.M. PUTU 90 maize crop growth model, user instructions and model decription. Department Agro-meteorology. University of the Orange Free State for Summer Grain Centre. Department of Agriculture and Water Supply. Bloemfontein., 1989.

Du Toit, A.S., Booysen, J. and J.J., Human. Evaluation and calibration of CERES-Maize. 3. Row widths for the western Highveld *S.Afr. J. Plant Soil* (4), 153-158, 1994

Edmeades, G.O. and T.B. Daynard, The development of plant-to-plant variability in maize at diffirent planting densities. *Can.J. Plant. Sci.* 59,5761-576, 1972.

Grant, R.F. Simulation of carbon assimilation and partitioning in maize. *Agr. J,* 563-571, 1989.

Hall, A.J. , Chimenti, C., Trapani, N. , Vilella, F. Cohen and R. de Hunau. Yield in water stressed maize genotypes: Association with trials measured in seedlings and in flowering plants *Field Crops Res., 9, 41-57*, 1984

Herrero, M.A and R.R. Johnson. Drought stress and its effects on maize reproductive systems. *Crop Sci.* 21,105-110, 1981.

Jones, C.A and J.R. Kiniry. CERES-Maize: A simulation model for maize growth and development. Texas A & M University Press, College Station, 194 pp., 1986.

Keating, B.A., McCown, R.L. & B.M. Wafula. Adjustment of nitrogen inputs in response to a seasonal forecast in a region of high climatic risk. *In:*

System approach for Agricultural Development, 1993. F.W.T. Penning de Vries *et al. (eds.).* Kluwer academic Publishers. Netherlands. pp 233-252, 1993.

Mallett, J.B. The use of climatic data for maize grain yield predictions. PhD. thesis University of Natal. Pietermaritzburg. 1972.

Ogoshi, R.M. Determination of Genetic Coefficients from yield Experiments for CERES-Maize and Soygro crop Growth Models. PhD dissertation, University of Hawaii, Honolulu, Hawaii. pp 189, 1995.

Otengui, M.E, Andrade, F.H. and E.E. Suero. Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Res.* 40, 87-94, 1995.

Schussler, J.R. and M.E., Westgate. Maize kernel set at low water potential: I. Sensitivity to produced assimilates during early kernel growth. *Crop Sci.* 31,1189-1195, 1991.

Spitters, C.J.T., Van Keulen, H. and D.W.G Kraalingen. A simple and universal crop growth simulator: SUCRO87. *In:* Rabbinge, R, Ward, S.A and van Laar, H.H. (eds.) Simulation and systems management in crop protection. Simulation Monographs 32. Pudoc Wageningen 1989.

Stapper, M., and G.F., Arken. CORNF: A dynamic growth and development model for maize. Res. CTR., Temple, TX 76503), TX Agric. exp. Sta, 1980.